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ABSTRACT

The Defense Nuclear Agency (DNA) Kinetic Energy Weapon Lethality and Target Hardening Program (LTH-5) has studied hypervelocity impacts on simple and complex targets for a number of years on behalf of the Strategic Defense Initiative Organization (SDIO). The test parameter space includes projectile masses from 0.1 - 93 grams and velocities ranging from 1 - 9 km/s. The work to date includes experimentation and modeling and the resulting data and codes can be made available to the Orbital Debris Spacecraft Breakup Modeling Program through technology transfer. This will reduce duplication, conserve scarce R&D funds, and provide a head start to orbital debris breakup modeling efforts. This paper highlights results from those LTH-5 activities which will be of most interest to those involved with orbital debris generation and the effects of debris on spacecraft. The attached bibliography documents some LTH-5 efforts which are directly applicable to orbital debris breakup modeling.

Nomenclature (Acronyms)

AFATL	Air Force Armament Laboratory (Eglin AFB, FL)
AFB	Air Force Base
AFSTC	Air Force Space Technology Center (Kirtland AFB, NM)
ASAT	Antisatellite
DNA	Defense Nuclear Agency
DoD	Department of Defense
DoT	Department of Transportation
DST	Defense Suppression Threat (ASAT weapon)
EPSA	Elasto Plastic Shell Analysis
HE	High Explosive
HVI	Hypervelocity Impact
ICBM	Intercontinental Ballistic Missile
IG	Interagency Group
KAPP	Kaman Analytic Penetration Program
KEW	Kinetic Energy Weapon
KKV	Kinetic Kill Vehicle
KNAPP	Kaman New Analytic Penetration Program
KSC	Kaman Sciences Corporation
LTH	Lethality and Target Hardening
LTH-5	Kinetic Energy Weapon Lethality and Target Hardening
NASA	National Aeronautics and Space Administration
NRL	Naval Research Laboratory (Washington, D.C.)
PIP	Propellant Initiation Program
R&D	Research and Development
SAIC	Science Applications International Corporation
SDIO	Strategic Defense Initiative Organization
SLBM	Submarine-Launched Ballistic Missile
USASDC	U.S. Army Strategic Defense Command (Huntsville, AL)

I. Background

The objective of the SDIO/DNA Kinetic Energy Weapon (KEW) Lethality and Target Hardening (LTH) Program is to provide kinetic energy weapon designers with lethality criteria and assessment tools. These tools are

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needed to address the many kinetic energy fluences possible on a variety of aerospace targets to allow the weapon designer to develop a robust, effective system. The LTH-5 Program is balanced between experimental testing and analysis and modeling. The experimental test program conducts hypervelocity impact tests and ground simulations of KEW intercepts. The data collected are then placed in an impact phenomenology database. The analysis and modeling program analyzes the data, develops predictive models, establishes lethality criteria, and conducts lethality assessments. Much of the test data and several predictive models are directly applicable and available to the Department of Defense (DoD) Orbital Debris Spacecraft Breakup Modeling Program through technology transfer.

A brief history of the DoD Orbital Debris Program is presented here to show the program's genesis and history. In February 1987, Secretary of Defense Weinberger signed a DoD Space Policy document calling for the minimization of space debris consistent with mission requirements. This was followed by a National Space Policy document signed by President Reagan in January 1988. This document was the first official U.S. Government recognition of orbital debris as a problem. The National Space Policy Document directed the formation of an Interagency Group (IG) to study the debris problem and make recommendations. The IG (Space) Report was endorsed by the National Security Council in February 1989. It recognized orbital debris as a growing problem and recommended DoD, NASA, and DoT develop research plans to address orbital debris. These agencies developed a coordinated, two-phase research plan (published May 1990 and endorsed by the National Space Council July 1990) to mitigate future generation of debris and enhance spacecraft survivability. The Spacecraft Breakup Modeling Program began the process of coordinating the related activities of various DoD agencies in November 1990. The program is now able to accept LTH-5 data through technology transfer.

Orbital Debris Modeling Program

The objective of the DoD Orbital Debris Spacecraft Breakup Modeling Program is to develop spacecraft and target response models for use in: 1) determining generated debris populations for on-orbit encounters or engagements, 2) mitigating the future generation of debris, and 3) hardening satellites to make them more survivable. Figure 1 contains the main elements of the Breakup Modeling Program, including technology transfer. DoD users have been identified and their requirements are being defined. Users' needs range from very simple fast-running debris generation algorithms to very complex first-principles-based models for hardening/survivability. The Orbital Debris Modeling Program is committed to developing and validating impact and target response models to meet each user's need.

Trying to predict the impact and target response (including the generated debris cloud) of a highly nonsymmetrical satellite hit by some arbitrary piece of space debris is quite a technical challenge. To do this necessitates a well-balanced experimental and analytical program. The experimental test program will collect both phenomenological (how does the debris interact with the target and cause breakup) and statistical (what are the mass, size, and velocity vector distributions of the generated debris cloud) test data. Impact testing will range from simple flat-plate shotline tests backed by witness plates, to more complex shotline tests into components with debris catchers, on up to actual satellite impact tests with special debris *soft catch* instrumentation. The modeling part of the program will consist of: 1) the development and validation of simple empirical breakup models and 2) complex first-principles analyses to help understand basic phenomenology. These efforts will rely heavily on the impact test data.

II. Lethality Experiments

This section describes five completed or upcoming LTH-5 tests where high-fidelity targets are impacted or experience simulated impacts by hypervelocity kinetic energy projectiles. After each test, a target lethality assessment is performed and debris are collected and catalogued.

Defense Suppression Threat Tests

The LTH Program investigated the self defense effectiveness of a space-based kinetic kill vehicle (KKV) weapon against a direct-ascent (pop-up) antisatellite weapon, or defense suppression threat (DST). This investigation culminated with two scaled experiments of DST impacts. Experimenters fired a scaled interceptor at 5.5 km/s into a scaled mockup of the DST. Both the interceptor and DST hardware items were of multi-material construction. LTH experimenters collected and catalogued post-impact debris according to material and size.

Arena Test

The purpose of the arena test was to provide data to support assessment of the potential for neighboring weapon damage from initiation of the high explosive (HE) in the warhead of a weapon onboard a delivery system. The objective of the test was to characterize the debris from the detonation of the HE in a single weapon.

Understanding the fragmentation pattern and characteristics, and the blast environment is essential for accurate prediction of the damage to the remaining weapons. Appropriately scaled experiments and theoretical modeling have been employed to describe the interaction; however, full-scale experiments are required to validate and benchmark the models.

The arena test was conducted in August 1989. The test consisted of the initiation of the high explosive portion of an otherwise inert warhead in a hemispherical pit. Test data were collected with velocity screens, fragment collection bundles, time-of-arrival pins, 450 keV flash x-rays, high-speed cinematography (2000-16,000 frames/second), and pressure and strain gauges. LTH analysts catalogued test data according to fragment material, size, velocity, and spatial distributions.

Donor/Acceptor Test

Two or three full-scale, high-fidelity weapons will be placed in a threat delivery system configuration. One weapon (the donor) will be detonated to simulate a fragment impact from a KKV. The acceptor weapon(s) will be instrumented to determine if the high explosive in their warhead(s) detonated. Experimenters will field instrumentation to collect data on the generated debris cloud and collect, measure, and weigh debris pieces after the test.

Propellant Initiation Program Tests

The purpose of the propellant initiation program (PIP) is to assess the potential for weapon damage from initiation of a hypergolic reaction in the propellants onboard a threat delivery system when it is impacted by a kinetic kill vehicle. LTH-5 has scheduled the full-scale PIP test to address this issue. The objectives of the test are to determine the number and type of mechanisms causing weapon damage resulting from hypergolic propellant interactions, determine the degree of mixing of hypergolic propellents, establish a database from which damage prediction models can be developed, and quantify the extent of damage to weapons.

The test will consist of a full-scale, high-fidelity threat delivery system containing live propellants and instrumented but inert weapons. A tailored high explosive charge will simulate a hypervelocity impact of a KKV into a target's oxidizer tank. Subsequent damage to the weapons will recorded and assessed.

The full-scale, high-fidelity was preceded by a low-fidelity, risk reduction pilot test, in which the weapons were omitted. The pilot test was performed, at the Astronautics Laboratory, Edwards Air Force Base, CA, to characterize the environment and verify the instrumentation to be employed in the PIP test. The debris collected from the PIP pilot test is shown in Figure 2.

SLBM Impact Tests

The test series will involve two high-fidelity scaled SLBM threat delivery systems that will be impacted by KKV projectiles developed for this and future impact tests.

Instrumentation fielded in this test series will include flash x-rays, laser photography, and rotating mirror (Beckman & Whitley) high-speed cameras for visual inspection of the impact event. Also, pressure transducers and time-of-arrival pins mounted on the high-fidelity weapons and delivery system chassis will record pressure and time-of-arrival data. Padding will be placed below the suspended target to protect test article components from post-impact damage. Experimenters will collect and catalog debris from the tests.

Bibliography of Experimental Data and LTH Analyses

A bibliography, attached as an appendix to this paper, contains LTH-5 reports which have direct application to orbital debris breakup modeling. McKnight and Brechin of the U.S. Air Force Academy Department of Physics prepared several reports of their debris analyses sponsored by AFATL which are contained in this bibliography. Another bibliographical reference refers to the recent debris characterization test series conducted at the Naval Research Laboratory (Williams and Saravane, 1990). The report speaks for itself and will not be repeated here. However, the scope of the work should be mentioned in order to illustrate the relevance for orbital debris research. NRL varied the projectile mass, material velocity and impact angle as well as the thickness of the target shatter plate. Data from each of the ten experiments is presented in the final report. In some shots, NRL has catalogued over three hundred individual fragments. Raw data includes impact location and crater depth and major and minor diameters. Calculations include crater volume and projectile mass, diameter and residual velocity.

III. Lethality Hypervelocity Penetration Models

This section describes the KAPP and KNAPP models which LTH-5 analysts developed to calculate the response of targets to a variety of kinetic energy fluences.

KAPP Model

The Kaman Analytic Penetration Program (KAPP) is a fast-running, semi-empirical computer code designed to predict penetration depth and hole size in three-dimensional, multi-material targets impacted by an arbitrary number of chunky (length-to-diameter ratio of about one) projectiles. KAPP was developed by Kaman Sciences Corporation, Colorado Springs, CO, under contract to the U.S. Army Strategic Defense Command (USASDC), Huntsville, AL, as a tool to predict damage to targets when impacted by strategic defense kinetic energy weapons.

KAPP consists of a number of simple models which have been combined with ray trace and damage assessment routines. It handles approximately 400 projectiles per minute on a VAX-class computer (Greer *et al.*, 1989). The SDIO KEW Lethality Program has used KAPP to generate probability of kill (P_k) assessments.

KAPP has been calibrated with an extensive database developed from two-stage light gas gun testing and hydrocode calculations. This database covers a wide range of impact conditions ranging from 2 to 9 km/s, the current limit of gas gun technology (Greer, *et al.*, 1989).

In the early 1980s, Dr. Peter Snow of Kaman Sciences Corporation developed the original KAPP code to predict penetration depth and hole areas in compact (relatively short stand-off distances) targets. Since that time, KAPP has been modified and enhanced and modified according to program needs and technology improvements.

When executing KAPP for a particular *target engagement* pair, the first step performed is a ray trace. Targets can be described in the GIFT (Bain, 1975) or FASTGEN (Cudney, 1978) combinatorial geometry packages. Ray traces through GIFT or FASTGEN target descriptions provide material thicknesses and descriptions of each layer intersected by a projectile's flight path.

Figure 3 shows a representative ray trace through a KAPP target and the KAPP algorithms which would be invoked. Ricochet is simulated by a mass reduction and trajectory change of the incident projectile. The penetration into the layer is calculated using the Dehn (Dehn, 1986) penetration algorithm. This algorithm calculates projectile penetration accounting for target hardness and inertial resistance.

If the penetration exceeds 75% of the layer thickness, the layer is assumed to be perforated. This is a simple way of accounting for back face phenomena effects such as spall, petalling, and scabbing. The penetration and regular hole algorithms are invoked for subsequent layers of the target until the projectile comes to rest or exits the target (Greer, *et al.*, 1989).

When a projectile perforates a target plate, the algorithms are performed on subsequent layers of the target using the residual velocity after penetrating the first layer. If a projectile crosses a void before striking the next layer of the target, the density is reduced to account for debris spread. This density reduction is controlled by the void space distance and debris spread angle (Greer, *et al.*, 1989).

KAPP simulates oblique impacts using two techniques. The shotline thickness is used as the layer thickness. Second, projectile mass is reduced to account for ricochet (first layer only). This algorithm is exercised for impacts less than 50^{o} (90^{o} is a normal impact) and is based on hydrocode calculations (Greer, *et al.*, 1989).

Hypervelocity impact craters in semi-infinite targets are hemispherical when the target and impactor consist of the same materials. Impacts of low-density projectiles on high-density targets produce craters with a flattened cross section. Conversely, high-density projectile impacts on low-density targets have a deepened cross section. KAPP relates crater radius at the top of the layer to penetration depth as a function of projectile and target densities (Greer, *et al.*, 1989).

In plate targets, hole sizes increase with respect to the ratio of plate thickness to projectile radius, up to a limit. Hole sizes then decrease with respect to the same ratio until the ballistic limit is approached. KAPP assumes that perforation of a plate of zero thickness will create a hole with radius equal to the projectile radius. As the layer thickness increases, the crater radius increases to the limit of the semi-infinite crater radius. In between, hole sizes are governed by other empirical equations (Greer, *et al.*, 1989).

In oblique impacts, holes are elliptical in shape. KAPP determines hole diameters perpendicular to the impactor flight path as discussed above. The length of the hole is influenced by the projection of the damage at normal incidence onto the plate at the impact angle (Greer, *et al.*, 1989).

KNAPP Model

In order to be able to predict damage to targets with large voids or stand-off distances, AFATL, Kaman Sciences Corporation, and Science Applications International Corporation modified KAPP. The modified code, KNAPP (for Kaman New Analytic Penetration Program), is able to predict

off-shotline damage which is caused by debris effects. The KNAPP code fragments the incident impactor (and applicable target material) into a discrete number of secondary projectiles (user specified). KNAPP tracks these projectiles and calculates target damage. KNAPP runs slower than KAPP because it tracks many fragments in performing its damage calculations (see Figure 4).

IV. Structural Response Codes

EPSA

At the request of DNA, Weidlinger Associates undertook a series of calculations using the Elasto Plastic Shell Analysis (EPSA) finite element code (Smilowitz, 1989).

The code, developed for DNA has been verified many times by comparing pre-test predictions with actual test results over a large range of loading conditions and structure types. It was anticipated that EPSA would provide a means of quickly varying threat loadings to assess the sensitivity of a complex target's structural response. Parameters that could be varied included geometry, connections, materials, and mass in the target as well as magnitude and orientation of the loadings and phasing of multiple loadings. In order to determine the utility of EPSA to LTH-5, it calculated the structural response of a threat delivery system to loadings from propellant initiation. Preliminary tests were conducted at quarter scale and the EPSA code was initially exercised at load levels measured in these tests. Subsequently, the code predicted the response at full scale in anticipation of the upcoming PIP test. This approach shows considerable promise for both the LTH-5 and orbital debris breakup programs. EPSA is available now, relatively inexpensive to use, extremely flexible and relatively accurate. It offers the analyst a tool to quickly assess the sensitivity of complex space targets to hypervelocity impacts over a wide range of conditions.

V. Coupled Hydro/Structural Codes

SAIC

Hydrodynamic codes have been developed and validated which effectively model the early-time, localized material responses to hypervelocity impacts in complex targets. Unfortunately, such codes are unsuitable to study the late-time structural response to such impacts due to the rapid propagation of damage over large areas. Another set of reliable, validated finite element codes exists which model a structure's response to shock loading. Structural response codes, however, are not entirely appropriate for orbital debris work since the loading is from high-velocity impact and not shock. Bob Bjork of Science Applications International Corporation (SAIC) has suggested a combination of hydrocode and structural response codes for similar problems (Bjork, 1990)

Bjork's suite of codes include hydrocodes PEACH2D and PEACH3D and structural response codes STAGS and DYNA3D. He developed a code TRANSPORT to provide the transition between the localized, high-pressure, high-density, short time hydrocodes and the finite element codes with special elements for approximating the response of individual components of the structure. He used his codes to replicate a scaled kinetic kill vehicle impact at 5.7 km/s with a scaled threat delivery system model.

KSC

Vernon Smith of Kaman Sciences Corporation has undertaken another coupled code approach on behalf of the Air Force Armament Laboratory and the Air Force Space Technology Center (Smith, 1990). This modeling effort centers on the interface between the SOIL3D hydrocode and the ABAQUS structural response code. Figure 5 illustrates the process of converting the debris calculated by SOIL to a loading input for ABAQUS. The novel transport code, DEBRIS, provides a series of segmented solid angle quills, one for each azimuth and declination. Such a scheme permits quill momentums to be applied to ABAQUS element centers as impulse loadings. Each quill segment time of arrival is determined by its radial velocity distribution and the pulse width is calculated on radial segment density and velocity distributions.

A separate but related problem is one of debris fragment sizes, mass and velocity distributions; this is of particular interest to the orbital breakup problem. Strain rate information is collected from both SOIL and ABAQUS and used in Grady models to predict the characteristic diameter of fragments produced during the projectile target interaction. Refinement of modeling techniques continues. Data are required for geometries and material properties under high-velocity impact conditions. Presently only spheres, square plates, and disks have been proposed for study. Model decisions must be made regarding the choice of ductile or brittle materials, ductile or brittle failures and the magnitudes of strain rates. Preliminary versions of the completed suite of codes are able to approximate test data on very simple experiments.

VI. Summary

We have presented examples of technology transfer from the SDIO/DNA KEW Lethality and Target Hardening Program to the DoD Orbital Debris Spacecraft Breakup Modeling Program. An annotated LTH-5 bibliography has been provided which contains the sources for the debris data and models of interest. The Orbital Debris Modeling Program has a strong need for accurate debris data and views the LTH-5 Program as a valuable data source. This type of technology transfer will result in a more cost- and performance-effective Orbital Debris Breakup Modeling Program.

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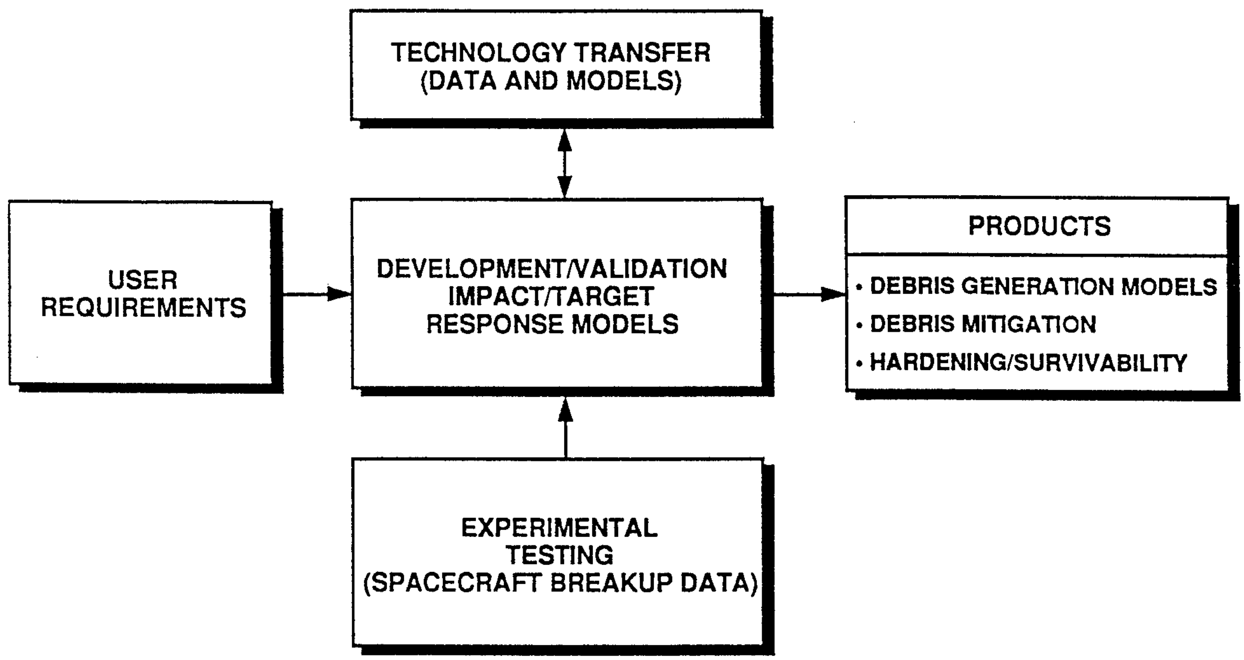
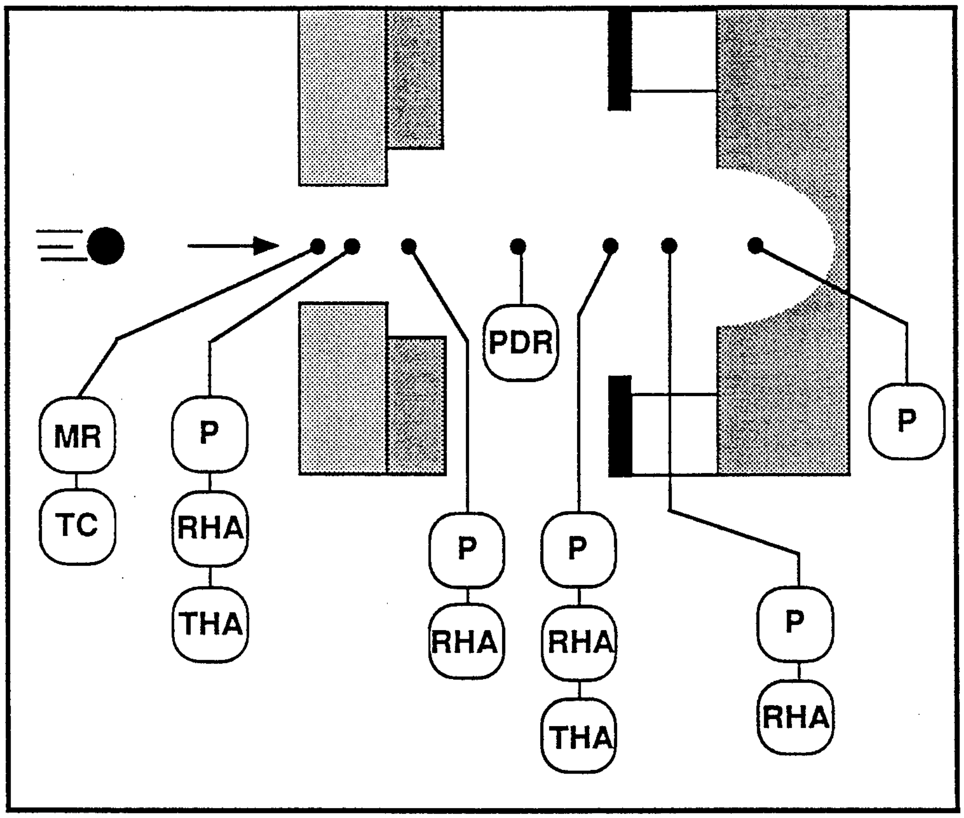


Figure 1. Elements of the Orbital Debris Breakup Modeling Program.

Figure 2. Post-test photograph of the Pilot Test article (Source: Eacret, 1990).



Key: MR Mass Reduction
P Penetration
PDR Projectile Density Reduction
RHA Reqular Hole Area
TC Trajectory Change
THA Total Hole Area

Figure 3. KAPP algorithm usage (Source: Greer, *et al.,* 1989).

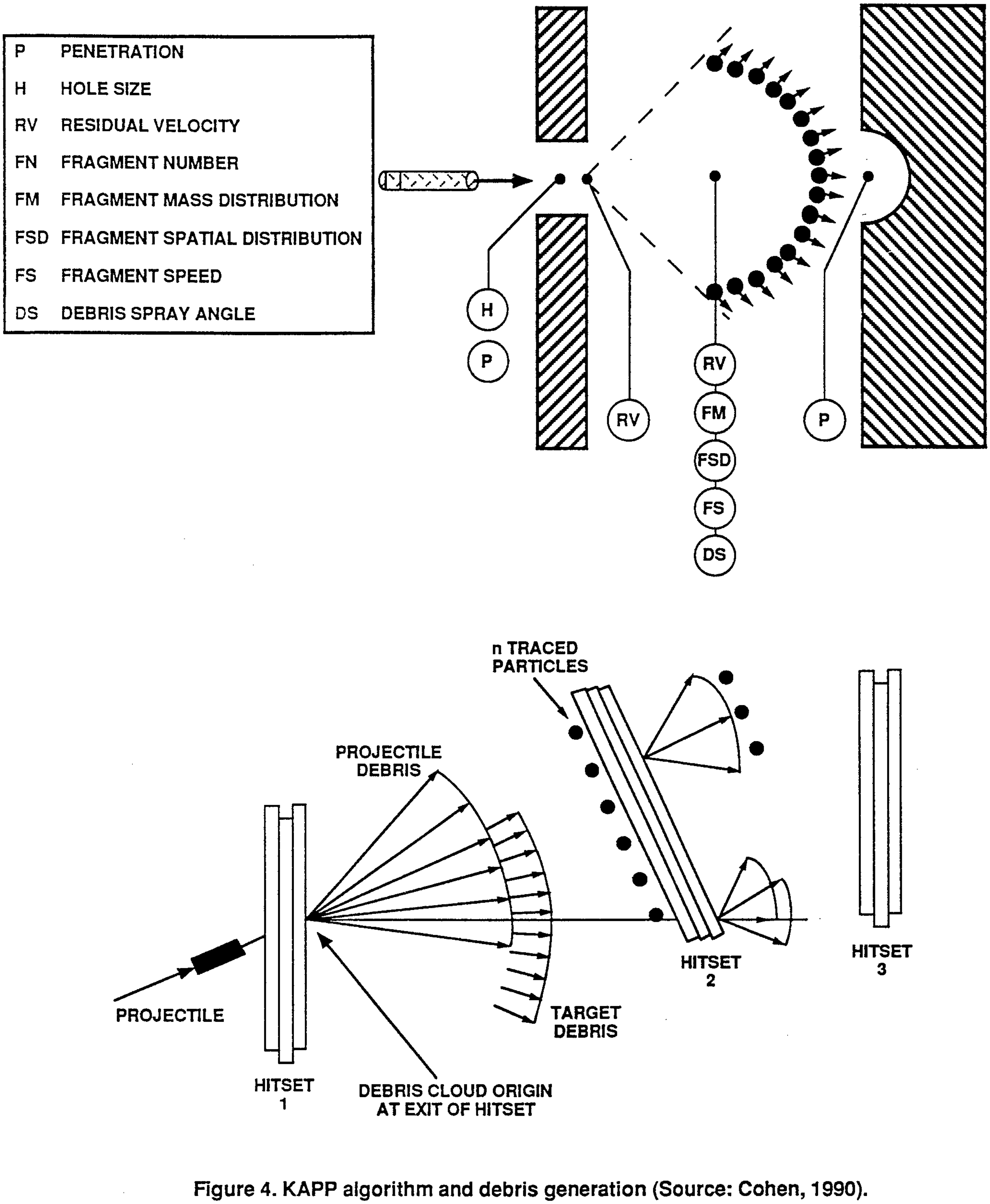


Figure 4. KAPP algorithm and debris generation (Source: Cohen, 1990).

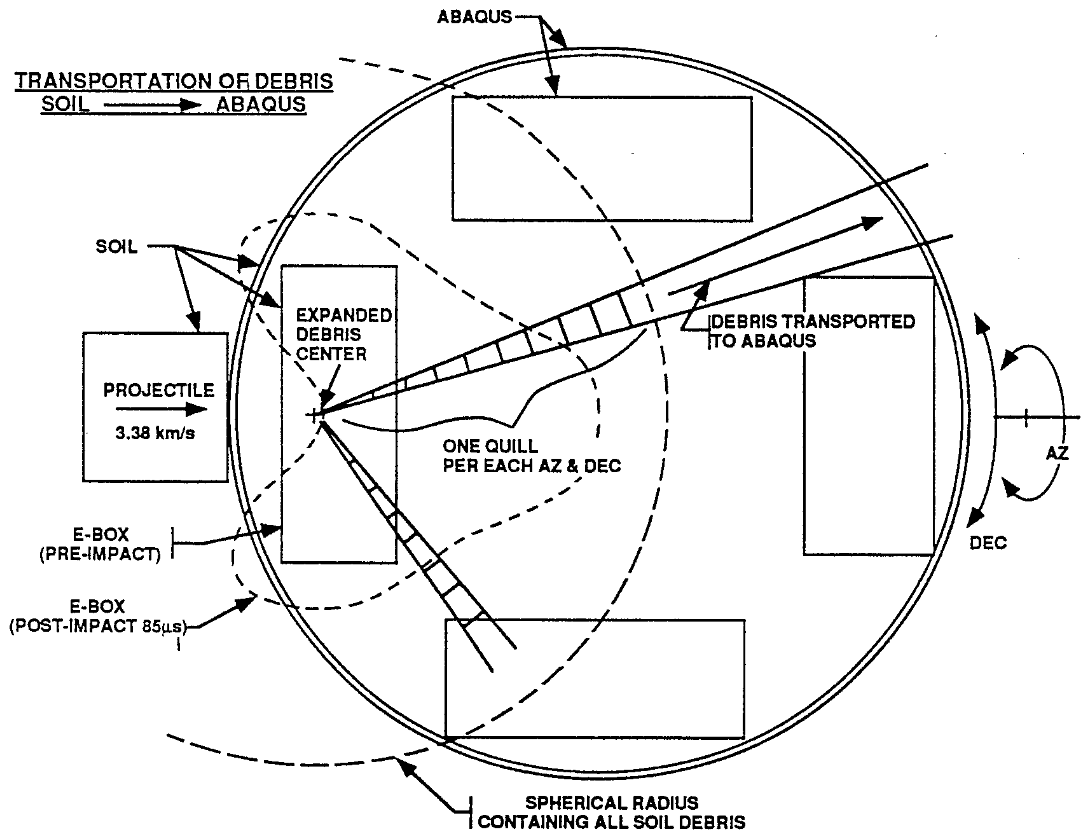


Figure 5. Schematic of the KSC coupled hydro/structural code approach (Source: Smith, 1990).

APPENDIX

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